Journal of Forestry Research (2013) 24(4): 677−682
DOI 10.1007/s11676-013-0404-3

ORIGINAL PAPER

Carbon storage in evergreen broad-leaf forests in mid-subtropical region of China at four succession stages

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Received: 2012-10-28; Accepted: 2013-02-14

Abstract: To better understand the effect of forest succession on carbon sequestration, we investigated carbon stock and allocation of evergreen broadleaf forest, a major zonal forest in subtropical China. We sought to quantify the carbon sequestration potential. We sampled four forest types, shrub (S_R), pine (*Pinus massoniana*) forest (P_F), pine and broadleaf mixed forest (M_F) and evergreen broadleaf forest (B_F). A regression equation was constructed using tree height and diameter at breast height (DBH) and elements of total tree biomass. The equation was subsequently utilized to estimate tree carbon storage. The carbon storage of understory, litter, and soil was also estimated. Carbon storage in biomass increased significantly from the early succession stage S_R (6.21 t·ha^{-1}) to the late stage B_F (134.87 t·ha^{-1}). The biomass carbon stock of forest layers generally increased with succession except for the understory. The soil organic carbon storage for the total profile increased with forest succession, from 51.16 to 90.49 t·ha^{-1}, but the contribution of SOC to the carbon stock of the forest ecosystem declined from 89.18% to 40.15%. The carbon stock at ecosystem scale increased significantly with succession from S_R (57.37 t·ha^{-1}), to P_F (154.20 t·ha^{-1}), to M_F (170.96 t·ha^{-1}) and to B_F (225.36 t·ha^{-1}), with carbon stock of B_F 3.93 times that of S_R. The forests in our study have great potential for increasing carbon sequestration, and large areas of secondary or degraded evergreen broadleaf forests in the subtropical zone of China could be a great carbon sink in future.

Keywords: Biomass carbon; Carbon allocation; Carbon sequestration; Soil organic carbon; China subtropical forest

Fund project: This study was supported by the "Strategic Priority Research Program" of the Chinese Academy of Sciences (XDA05050205) and “International Science & Technology Cooperation Program of China (2012DFB30030)” and “Youth Innovation Fund of Hunan Academy of forestry” and the CFERN&GENE Award Funds for Ecological Papers.
The online version is available at http:// www.springerlink.com

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Corresponding editor: Zhu Hong

Introduction

Forest ecosystems are a major sink of terrestrial carbon (C) (Dixon et al. 1994; Houghton et al. 2000), storing about 45% of terrestrial carbon, more than double the amount of carbon in the atmosphere (FAO 2006). In China, terrestrial ecosystems absorb 0.19-0.26 Pg C per year (Piao et al. 2009). Forests in southern China, after a large-scale forest restoration program, contributed about 65% of the carbon sink in southern China terrestrial ecosystems (Wang et al. 2009). Enhancing carbon storage in forest ecosystems will be a key factor in the maintenance of the global atmospheric carbon balance. Forest succession can have a remarkable effect on the carbon contents in the ecosystem. Forest succession can capture significant amounts of atmospheric carbon, and it is expected to contribute to soil quality (Zhang et al. 1999; Ouyang et al. 2003). However, the effects of forest succession on forest ecosystem carbon storage should not be neglected (Fang et al. 2003; Fonseca et al. 2011). To better understand restoration as an option for atmospheric CO_2 fixation and to understand the effects of succession on forest carbon storage, it is necessary to examine carbon pools and their changes.

The subtropical zone of China was originally covered by primary forests that were ultimately destroyed by human activities that intensified during recent centuries. Recently, forest restoration in the subtropical zone has received considerable attention.

This interest is emphasized in the policy of returning farmland to forest in the Yangtze River catchment. When human disturbance stops, the forest tends to naturally restore itself to the native state. Over the last few decades, subtropical secondary forests are rapidly being created through plantation, and most of them have undergone secondary forest succession. The main plantation species is masson pine (*Pinus massoniana*), which is used for timber and covers 3.27×10^{7} ha^{-1} in China (Kong and Mo, 2002). Among the studies of forest succession, many investigations have focused on the effects of forest succession on soil fertility (Ouyang et al. 2003), biodiversity (Wang et al. 2007), and soil organic carbon (SOC) (Zhou et al. 2009). In contrast, few studies examined changes in carbon storage at various stages of succession in the forests of southern China. Quantifying the changes in the size of the carbon pool is fundamental for understanding the effects of forest succession on carbon dynamics. Therefore, studies are needed to estimate total carbon storage in forest ecosystems at various succession stages (Fang et al. 2003).

In this study, we measured and compared total ecosystem carbon in four forest types that represent four succession stages of forest recovery from shrub (S_R), to pine forest (P_F), to pine and broadleaf mixed forest (M_F), and finally to evergreen broadleaf forest (B_F). Our aim was to quantify changes in forest biomass carbon and soil carbon stock at each of these four stages of forest succession.

Materials and methods

Site description

The study area was in the Yingzuijie Biosphere Reserve (26°46′–26°59′N, 109°48′–109°58′E), Hunan Province. The Reserve lies at the transition zone from the Yunnan-Guizhou plateau to the lower mountains and hills on the southern side of the Yangtze River, at an elevation of 270–938 m above mean sea level. The climate of this region is humid mid-subtropical monsoon, with a mean annual temperature of 15.9°C. The mean annual precipitation is 1,400 mm, of which about 76% falls between April and August (Wang et al. 2005).

The reserve supports four types of natural vegetation communities: S_R, aged from 5 to 8 years, and dominant species including *Lithocarpus glabra, Loropetalum chinensis,* and *Maesa japonica*; P_F, aged from 30 to 35 years, and dominant tree species including *Pinus massoniana,* dominant shrub species including *Loropetalum chinensis, Rhus sylvestris and Camellia oleosa*; M_F, aged from 40 to 45 years, and dominant tree species including *Pinus massoniana, Castanopsis fargesii,* dominant shrub species including *Elaeocarpus sylvestris*, *Diospyros kaki var. silvestris and Smilax china*; B_F, aged from 60 to 65 years, and dominant tree species including *Castanopsis fargesii*, *Machilus pauhoi* and *Cyclobalanopsis glauca*, dominant shrub species including *Elaeocarpus sylvestris*, *Lindera glauca, Euonymus myrianthus and Smilax china.* Soils were predominantly derived from slate and shale, and are classified as Ultisols under the USDA taxonomy (Typic Paleudults).

Biomass estimation

From May to July 2010, three 20 m× 20 m plots were established at each forest site. We measured diameter at breast height (DBH) at 1.3 m height, tree height, and crown length of all trees on the three plots in each stand. We harvested 15 *Castanopsis fargesii,* 19 *Machilus pauhoi,* 21 *Cyclobalanopsis glauca,* 25 *Pinus massoniana*, and 32 of other non-dominant species in experimental zones of Nature Reserves based on the distribution of the measured DBH values. After a tree was felled, we measured total height with a steel tape (accurate to 0.1 m). Each bole was then cut into 2-m sections, and each section was separated into stem, bark, leaf and branch. Roots were also excavated to a depth of 100 cm. Excavations were centered on the stumps of the harvested trees. Roots from the harvested tree were collected and washed. All components were dried at 80°C to constant weight. The dry weights of standing individuals in the sampling stands were estimated by means of allometric regression equations for individual trees. We then used this equation to calculate the aboveground biomass of each tree and the total aboveground biomass for each stand (Wang et al. 2009).

Understory biomass was determined using destructive sampling techniques (i.e., total harvesting, including roots), within five randomly selected 4 m× 4 m subplots within each of the 20 m× 20 m plots. A total of fifteen 4 m× 4 m plots were sampled in each forest type. Forest detritus (i.e., litter and coarse wood) were sampled within six 1 m× 1 m subplots randomly chosen in each 20 m × 20 m plot. A total of eighteen 1 m× 1 m subplots were sampled in each forest type. All plant materials collected within these 1 m× 1 m subplots were sorted into two components: Coarse wood with a diameter greater than 2 cm and height at least 40 cm and litter (leaves and twigs). Forest detritus was bagged separately and transported to the lab (Wang et al. 2009).

Mineral soil sampling

Soil cores were collected using a stainless steel auger (5 cm internal diameter) at four depths of 0–10 cm, 10–20 cm, 20–40 cm, and 40–60 cm, from 10 random locations in each plot. All samples were transported to the laboratory and then air-dried for determination of carbon content. Soils were also assessed for bulk density with three bulk density corers at the same depth range. Rocks and gravel (>2 mm diameter) were sieved from each soil sample and weighed to estimate the content of gravel in soil. This work was conducted based on Forestry Standards “Observation Methodology for Long-term Forest Ecosystem Research” of People’s Republic of China.

Sample analyzing and carbon calculation

The samples of soil and biomass were ground in preparation for analysis of carbon concentration using a C/N analyzer (Elementar, Germany). Mass of carbon stored in tree components, understory vegetation, and forest floor was estimated by multiplying their measured biomass by their corresponding concentrations.

The total stock (S_{OCn} t·ha^{-1}) of soil organic carbon (SOC) to a depth of 60 cm was calculated based on the organic carbon content, sampled depth, and bulk density per Guo and Gifford (2002):

$$S_{ocn} = \sum_{i}^{n}(1-G_i)D_i \times C_i \times T_i / 10 \quad (1)$$

where, D_i (g·m^{-3}) is the soil bulk density of i layer, C_i (g·kg) is the soil carbon concentration of i layer, and T_i is the soil sampling depth (cm) of i layer, G_i is soil gravel content of i layer.

Statistical analysis

Data were analysed using SPSS Version 13.0 for Windows (SPSS Statistics, Shanghai, China). One-way analyses of variance (ANOVA) were used to test the differences in carbon concentrations, biomasses and carbon pools between the four succession stages. Least significant differences (LSD) were calculated when treatments were significantly different. Significance levels were set at α=0.05 in all statistical analyses.

Results

Biomass carbon pools

The total biomass pool increased significantly (p <0.05, Table 1) from early to late stages of succession. The biomass of stem wood, bark, branches, leaf, roots, and wood debris increased in the following order: $P_F < M_F < B_F$ (p <0.05, Table 1), and more than 50% of the biomass carbon appeared in stem wood in all stages. The biomass of the understory decreased with succession. The carbon concentration of biomass components decreased significantly except understory (p <0.05, Table 1) in the following order: $P_F > M_F > B_F$.

The understory had the lowest carbon concentration of all biomass compartments for these forests. Stem wood had the highest carbon concentration both in P_F and M_F while in B_F the highest was leaf. The carbon storage in biomass increased significantly (p <0.05, Table 1) with succession. The pools of carbon in stem wood, bark, branches, leaf, roots, and wood debris stock significantly increased in the following order: $S_R < P_F < M_F < B_F$ (p <0.05, Table 1). Stem wood accounted for 55.2% to 45.1% of the total biomass carbon storage in P_F and B_F, respectively, while the proportion of carbon stored in branches and roots increased from 12.5% to 16.4 % and from 12.9% to 17.3%, respectively, of total biomass carbon storage.

Mineral soil carbon pools

Soil bulk density in the upper two layers decreased significantly during the succession series (p <0.05), but showed no significant decrease in the lower two layers, increasing with soil depth. Generally, soil carbon concentration at all depths increased with succession (Fig.1) although significant increase was only found in the 0−10 cm depth (p <0.05). Carbon storage at 0−10 cm increased significantly with succession (p <0.05), but increased only slightly at deeper layers (Fig. 1). Additionally, there was an increasing trend in total soil carbon storage summed over the 0−100 cm depth with succession. About 70%−85% of the total soil carbon was stored in the top 40 cm of soil in these succession stages.

Table 1. Biomass (t·ha^{-1}), Carbon concentration (g·kg^{-1}), Carbon storage (t·ha^{-1}) of various compartments in the shrub (S_R), the pine forest (P_F), the pine and broad-leaf mixed forest (M_F) and the evergreen broad-leaf forest (B_F) in the Yingzuijie Biosphere Reserve, subtropical China..

Plot	Items	Stem wood	Bark	Branch	Leaf	Root	Wood debris	Understory	Litter	Total
S_R	Biomass	-	-	-	-	-	-	14.3(0.7)a	0.4(0.1)c	14.6(0.6)d
P_F		98.4(1.1)c	9.8(0.7)c	23.5(0.7)c	15.2(0.5)c	24.9(1.3)c	1.1(0.1)b	6.4(0.3)b	6.3(0.4)a	183.6(4.1)c
M_F		108.7(5.9)b	17.2(1.0)b	29.1(1.1)b	18.7(0.4)b	33.2(1.3)b	2.7(0.4)b	5.0(0.3)c	5.1(0.3)b	219.7(5.7)b
B_F		136.6(3.1)a	25.5(0.6)a	49.6(1.7)a	26.7(0.9)a	54.1(2.8)a	6.5(1.1)a	1.6(0.2)d	5.0(0.2)b	297.6(8.8)a
S_R	Carbon concentration	-	-	-	-	-	-	424.6(2.5)a	419.5(2.5)c	-
P_F		507.7(3.1)a	499.1(6.0)a	481.1(6.7)a	490.7(7.4)a	467.6(3.8)a	475.7(2.1)a	425.4(2.3)a	463.3(1.5)a	-
M_F		479.8(6.3)b	436.5(5.3)b	453.7(6.9)b	461.8(5.2)b	432.5(4.1)b	449.3(2.2)b	425.5(2.2)a	440.0(2.8)b	-
B_F		444.7(5.1)c	420.1(2.0)c	445.2(5.2)c	458.9(3.6)b	429.8(3.9)c	426.5(3.3)c	419.9(2.0)a	419.2(1.9)c	-
S_R	Carbon storage	-	-	-	-	-	-	6.1(0.3)a	0.2c	6.2(0.3)d
P_F		50.0(0.8)b	4.9(0.4)c	11.3(0.5)c	7.5(0.3)b	11.7(0.7)b	0.5(0.1)b	2.7(0.1)b	2.9(0.2)a	90.5(2.9)c
M_F		52.2(2.1)b	7.5(0.9)b	13.2(1.0)b	8.6(0.2)b	14.4(1.2)b	1.2(0.2)b	2.1(0.1)c	2.2(0.2)b	101.4(3.7)b
B_F		60.8(2.1)a	10.7(0.3)a	22.1(1.0)a	12.5(0.4)a	23.3(1.4)a	2.8(0.5)a	0.7(0.1)d	2.1(0.1)b	134.9(4.4)a

Notes: Data are means followed by standard deviations in the parentheses (n = 3). For each compartment, values with the different letters denote significant difference among forests at α=0.05 based on the least-significant-difference tests.

Carbon allocation

The carbon stock on ecosystem scale increased significantly with the succession from S_R (57 t·ha^{-1}), to P_F (154 t·ha^{-1}), to M_F (171 t·ha^{-1}), and to B_F (225 t·ha^{-1}) (Fig. 2). The combined carbon stocks in plant tissues and soils increased greatly but their individual contributions to the total carbon stocks of ecosystems varied greatly: the proportion of total carbon in plants increased quickly

with succession while that in soil gradually declined. Therefore, with succession from P_F to B_F, the plant carbon contribution to the ecosystem total was the most important, and that of soils was secondary. While ground cover was also important in S_R the most important was soil, followed by plant and ground cover.

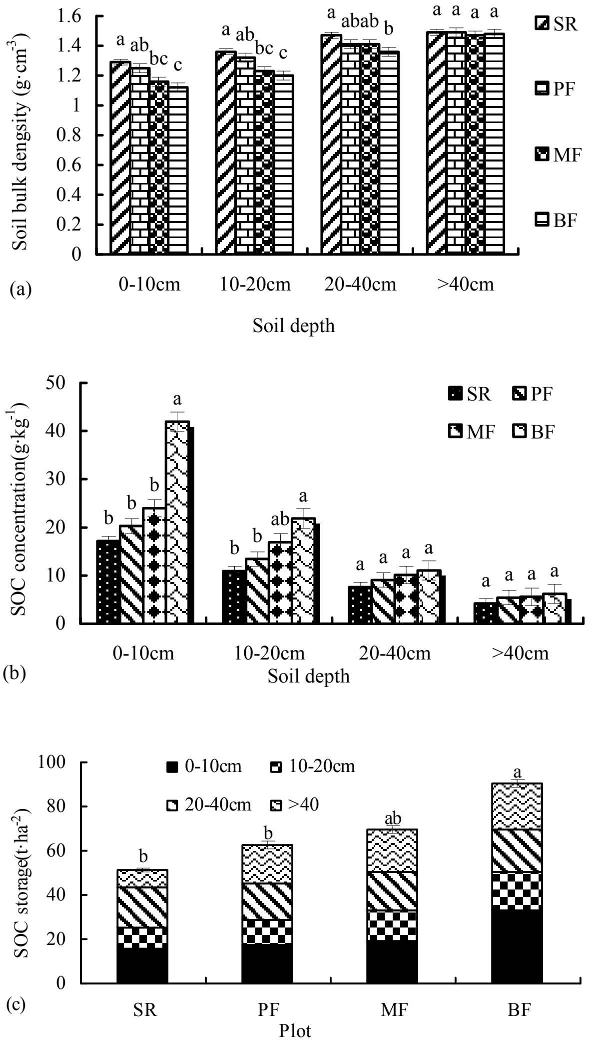

Fig 1. Soil bulk density (g·cm^{-3}), soil organic carbon (SOC) concentration (g·kg^{-1}) and soil organic carbon(SOC) storage (t·ha^{-1}) in the shrub (SR), the pine forest (PF), the pine and broadleaf mixed forest (MF) and the evergreen broadleaf forest (BF) in the Yingzuijie Biosphere Reserve, subtropical China. Vertical lines denote standard deviations. For each depth, values with the different letters denote significant difference among forests at α=0.05 based on the least-significant-difference tests.

Discussion

Biomass carbon storage

The biomass carbon stocks of studied forests were larger than the mean biomass carbon stock (57.07 t·ha^{-1}) of Chinese major forests (Zhou et al. 2000) because the studied forests in the reserve were subject to little anthropogenic disturbance. The biomass carbon stock of P_F in our study was similar to that at Dinghushan National Nature Reserve (90.06 t·ha^{-1}) (Fang et al. 2003), indicating that the weather and soils at Yingzuijie were useful for the accumulation of pine biomass carbon stock. Our biomass carbon stocks in M_F and B_F were lower than those reported for Dinghushan (M_F of 60–70 yrs, total carbon is 144 t·ha^{-1}; B_F of 400 yrs., total carbon is 180.52 t·ha^{-1}) (*ibid.*) because the M_F and B_F at Yingzuijie were not as mature as those at Dinghushan and would therefore be expected to continue sequestration of carbon in future years.

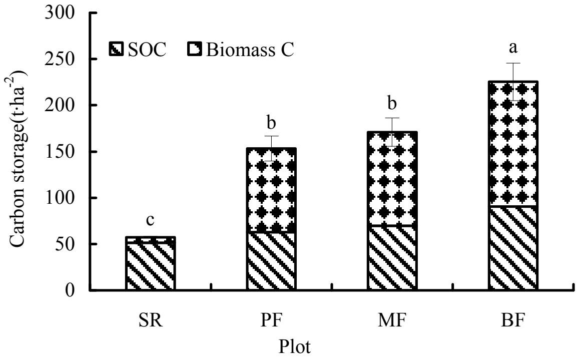

Fig 2. Carbon storage(t·ha^{-1}) in various components of each forests type in the shrub (SR), the pine forest (PF), the pine and broadleaf mixed forest (MF) and the evergreen broadleaf forest (BF) in the Yingzuijie Biosphere Reserve, subtropical China. Vertical lines denote standard deviations. Values with the different letters denote significant difference among forests at α=0.05 based on the least-significant-difference tests.

Natural forest succession was accompanied by a significant increasing trend in total biomass carbon stock (Table 1). The first and most important cause was the difference in the ages of these succession stages. Average DBH and tree height increased dramatically with forest age, and biomass increased accordingly. Secondly, different forest stages had different characteristics. Early succession stages were dominated by conifers (P_F), whose litter contains many phenolic compounds and lignin, both of which are N-poor and reduce decomposition rates (Scholes and Nowicki 1998). The broadleaf trees of M_F and B_F forests that replace the conifers produce N-rich litter that accelerates SOM decomposition, decreasing the thickness of the litter layer, and increasing overall vegetation biomass. Thirdly, succession increases in biomass can be explained by a mechanism called the competitive production principle (Kelty 2006). The species selection for and competition during restoration are among the main factors influencing ecosystem carbon sequestration (Lal. 2005). *Pinus massoniana* and the broadleaf trees can use site resources more efficiently in carbon fixation and subsequent growth because they occupy different ecological niches. Finally, as succession advances, forest biomass allocation shifts from stems to nutrition organs such as roots, leaf and branches (Table 1) that promote tree growth and add to biomass carbon storage.

Soil carbon storage

Our estimated range of SOC storage of 51−90 t·ha^{-1} was very similar to that reported for succession forest at a more northerly subtropical area in China (61.81 to 96.45 t·ha^{-1}) (Ma et al. 2010) and higher than in succession forests in more southerly subtropical China (39.8 to 77.6 t·ha^{-1}) (Fang et al. 2003). We estimated lower SOC storage for Yingzuijie forests than the mean SOC storage of east China forests (117.6 t·ha^{-1}) (Wang et al. 2000) and China forests (101.3 t·ha^{-1}) (Zhou et al. 2000). This result might be directly linked to the soil properties: the mean depth of soil in our study was no more than 60 cm, and the soil gravel content was 30%–40%.

In our study, the soil organic carbon concentration and storage tended to increase with forest succession, though the significant increases were only found in total SOC and the upper soil layer. The topsoil at 0−40 cm accounted for 72%–86% of the mineral soil carbon storage in Yingzuijie forests. This is consistent with the results of Xiao et al. (2007) who found that soil carbon in the 0−40 cm depth represented about 78% of total carbon storage in the upper 0−60 cm of soil. The changes in the carbon stocks of the upper soil layers in the different forest types reflect the differences in quantity and quality of litter input, and variations in litter carbon decay rates (Mo et al. 2002) and root biomass carbon (Wang et al. 2008).

Carbon allocation

With succession the total carbon storage of ecosystems increased from S_R (57 t·ha^{-1}), to P_F (154 t·ha^{-1}), to M_F (171 t·ha^{-1}), and to B_F (225 t ·ha^{-1}). carbon content increased by a factor of 3.93 between S_R and B_F but all estimates were lower than the mean carbon storage (258.83 t·ha^{-1}) reported for China forest ecosystem (Zhou et al. 2000) for low soil carbon storage in the studied plots.

Both soil and biomass contribute greatly to the increase of ecosystem carbon stock during succession but their proportional contributions varied by succession phase (Fig. 2). Forest succession was accompanied by a declining percentage of carbon stock in soils from 89.19% in S_R, to 41.34% in P_F, to 40.71% in M_F, and to 40.15% in B_F. Simultaneously, the percentage of carbon stock in biomass increased greatly and accounted for most of total ecosystem carbon stock in the climax phase. The soil layers of our studied plots were thin, with mean depth no more than 60 cm, and the content of gravel (>2cm) was about 30%–40%.

Wang and Feng (2000) reported that actual carbon storage in P_F, M_F, and B_F, when accounting for potential carbon storage, was 17.06%, 42.41%, 46.45%, respectively. In our study, there was a significant increasing trend in the total carbon pool during succession (Fig. 2). The increase in carbon was 97 (t·ha^{-1}) between S_R and P_F, 17 (t·ha^{-1}) between P_F and M_F, and 54 (t·ha^{-1}) between M_F and B_F. This suggests that with succession, there was substantial sequestration of carbon in plants, especially during early succession stages. In the subtropical zone of China, most of the secondary forests are in the prophase or pioneer succession stages. These forests should serve as a great carbon sink in the future. The next task would be to evaluate the relative importance of biomass and soil carbon sinks in mature forests and to estimate the volume of the carbon sink in secondary forests of the subtropical zones of China from our study results.

Conclusions

Forest succession was accompanied by significant increases in carbon storage in biomass and soils, and decreasing contributions of SOC to the total carbon stock of ecosystems. The carbon stock on ecosystem scale increased significantly with succession. In conclusion, our results suggest that the forests in our study would have great potential for increasing carbon sequestration in future and large areas of secondary or degraded evergreen broadleaf forests in subtropical zones of China will serve as a great carbon sink in the future.

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